EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATOR AND TECHNOLOGY SECTOR

CERN-ATS-2011-164

UPDATE ON COMPARISON OF THE PARTICLE PRODUCTION USING MARS SIMULATION CODE*

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In the International Design Study for the Neutrino Factory (IDS-NF), a 5-15 GeV (kinetic energy) proton beam impinges a Hg jet target, in order to produce pions that will decay into muons. The muons are captured and transformed into a beam, then passed to the downstream acceleration system. The target sits in a solenoid field tapering from 20 T down to below 2 T, over several meters, permitting an optimized capture of the pions that will produce useful muons for the machine. The target and pion capture systems have been simulated using MARS. This paper presents an updated comparison of the particles production using the MARS code versions m1507 and m1510 on different machines located at the European Organization for Nuclear Research (CERN) and Brookhaven National Laboratory (BNL).

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INTRODUCTION

In previous work [1] a significant difference between the particle yields, from simulations using exactly the same MARS [2] user input files, with version m1507 installed at CERN and BNL was found. This difference may be an issue for the optimization of the design of the IDS-NF [3] target station. The results from a detailed comparison between the two codes at CERN and BNL are summarized below. After the release of a new MARS version m1510, a comparison of the output yields from simulation using exactly the same MARS user input files at CERN and BNL was performed again, as well as a study of the difference in the particle yields between m1507 and m1510 at CERN. Whereas the codes are now in better agreement there is still some differences seen and their origin is investigated by the MARS code developers [4]. For the comparison study, runs of 10^5 protons on target were used, in the ST2 field map configuration (20 T solenoid field tapering down to 1.25 T, over 18 m).

M1507 AT CERN AND BNL

The MARS version m1507 was updated at CERN (July 21st, 2009) and BNL in 2009.

* Work supported by EU FP7 EUROnu WP3

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Comparison for different particle types

In Table 1 the energy setting with the largest deviation $\mid N_{CERN} - N_{BNL} \mid / N_{CERN}$, is given, for each particle type. Particle yields have been compared both at target (z = 0 m) and 50 m downstream of the target. The difference has been computed only when more than 100 particles were present at z = 0 m or 50 m. The details on the error calculations are given in [5]. The comparison results clearly show that the processes handling the production of photons, deuterium, protons, electrons and positrons are different at CERN and BNL. In addition the processes for neutrinos creation and tracking also seems to be different at BNL and CERN. The difference in the proton production is a problem for the estimation of particles that need to be removed from the accelerator systems or energy deposition calculations for the IDS-NF design study.

Table 1: Relative yield for m1507 at CERN and BNL.

Type	0 m	50 m
p	0.03 ± 0.01 (5 GeV)	0.25 ± 0.01 (7 GeV)
n	0.03 ± 0.01 (5 GeV)	-
π^+	0.12 ± 0.01 (5 GeV)	0.07 ± 0.02 (9 GeV)
π^-	0.04 ± 0.01 (7 GeV)	0.05 ± 0.02 (5 GeV)
K^+	0.13 ± 0.03 (8 GeV)	-
K^-	0.14 ± 0.07 (15 GeV)	-
μ^+	0.10 ± 0.07 (8 GeV)	0.05 ± 0.01 (6 GeV)
μ^-	0.10 ± 0.08 (7 GeV)	0.06 ± 0.01 (14 GeV)
γ	0.03 ± 0.03 (6 GeV)	97.4 ± 46.7 (14 GeV)
e^-	0.04 ± 0.02 (5 GeV)	0.19 ± 0.02 (14 GeV)
e^+	0.07 ± 0.02 (8 GeV)	0.21 ± 0.02 (7 GeV)
d	0.41 ± 0.06 (5 GeV)	0.32 ± 0.14 (6 GeV)
ν_μ	0.07 ± 0.03 (12 GeV)	0.33 ± 0.08 (5 GeV)
$\bar{\nu}_\mu$	0.14 ± 0.04 (12 GeV)	0.20 ± 0.07 (15 GeV)
ν_e	0.19 ± 0.05 (9 GeV)	-
ν_τ	0.15 ± 0.05 (9 GeV)	-

Muons yield in the Neutrino Factory acceptance

As a figure of merit of the muons accepted by the Neutrino Factory front-end (buncher, rotator and cooler), the muons yield, for $40 < E^{\mu}_{kin} < 180$ MeV is computed at z = 50 m. A comparison between yields from BNL and CERN simulations is given in Fig. 1. Even though m1507 at CERN and BNL seems to have different processes present, the muon production, in the Neutrino Factory acceptance

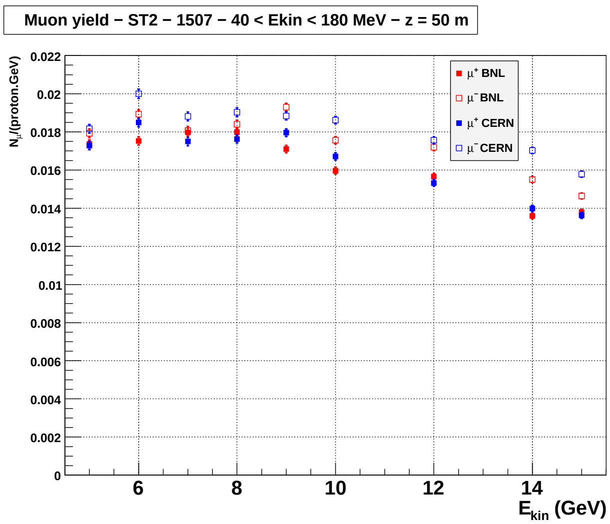

Figure 1: Muon yield normalized to the beam power (per proton and per GeV), as a function of the proton beam kinetic energy.

does not seem to be affected and the difference in the relative yield $\mid N_{CERN} - N_{BNL} \mid / N_{CERN}$ within the acceptance cuts is below 10%.

M1507 AND M1510 AT CERN

The MARS version m1510 was installed at CERN (February 11th, 2011) and BNL in 2010.

Comparison for different particle types

In Table 2 the energy setting with the largest deviation $\mid N_{1507} - N_{1510} \mid / N_{1507}$ is given, for each particle type. Particle yields have been compared both at target (z = 0 m) and 50 m downstream of the target, for beam kinetic energy between 5 and 15 GeV. The difference has been computed only when more than 100 particles were present at z = 0 m or 50 m. The two versions are giving yields in agreement, except for K^+, μ^+ at z = 0 m and photons at z = 50 m (but within large errors bars). The $\bar{\nu}_\tau$ yield at z = 0 m and the $\nu_\mu/\bar{\nu}_\mu$ yields at z = 50 m are also presenting some difference. This is probably due to modifications of the physics processes between the m1507 and m1510 versions.

Muon yield in the Neutrino Factory acceptance

For MARS versions m1507 and m1510, a set of 50 runs with different starting seeds (using a random generator) has been computed, for beam kinetic energy between 5 and 15 GeV. The distribution of the muons with $40 < E^{\mu}_{kin} <$ 180 MeV has then been used for each energy setting, in order to compute the mean and the standard deviation of the distribution. On Fig. 2 the mean (open of filled squares) and the standard deviation (error bars) are given for each energy bin computed. MARS versions m1507 and m1510 are giving very similar yields within the acceptance cuts.

Table 2: Relative yield at CERN for m1507 and m1510.

Type	0 m	50 m
p	0.03 ± 0.01 (7 GeV)	0.11 ± 0.01 (7 GeV)
n	0.02 ± 0.01 (7 GeV)	-
π^+	0.03 ± 0.01 (7 GeV)	0.07 ± 0.02 (6 GeV)
π^-	0.02 ± 0.01 (7 GeV)	0.09 ± 0.02 (5 GeV)
K^+	0.22 ± 0.03 (15 GeV)	-
K^-	0.13 ± 0.07 (15 GeV)	-
μ^+	0.19 ± 0.08 (8 GeV)	0.06 ± 0.01 (7 GeV)
μ^-	0.13 ± 0.08 (5 GeV)	0.04 ± 0.01 (7 GeV)
γ	0.07 ± 0.02 (8 GeV)	0.68 ± 0.63 (15 GeV)
e^-	0.05 ± 0.02 (6 GeV)	0.05 ± 0.02 (6 GeV)
e^+	0.10 ± 0.02 (10 GeV)	0.08 ± 0.02 (10 GeV)
d	0.15 ± 0.05 (15 GeV)	0.21 ± 0.13 (7 GeV)
ν_μ	0.08 ± 0.03 (5 GeV)	0.34 ± 0.08 (5 GeV)
$\bar{\nu}_\mu$	0.10 ± 0.05 (5 GeV)	0.39 ± 0.11 (7 GeV)
ν_e	0.27 ± 0.05 (15 GeV)	-
ν_τ	0.47 ± 0.06 (12 GeV)	-
$\bar{\nu}_\tau$	0.62 ± 0.17 (15 GeV)	-

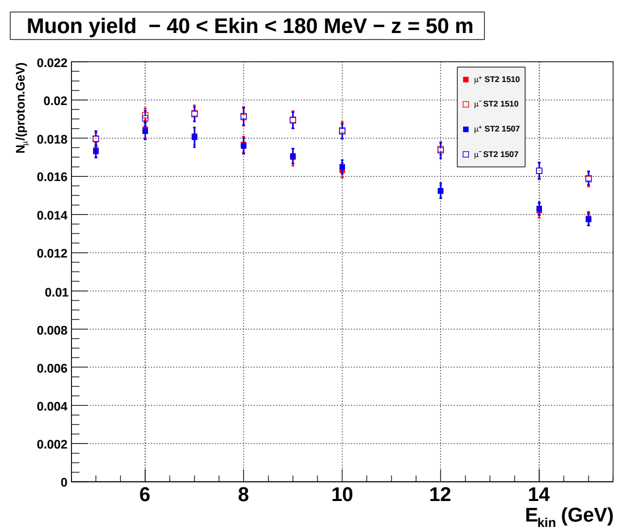

Figure 2: Muon yield from 50 runs, normalized to the beam power (per proton and per GeV), as a function of the proton beam kinetic energy.

M1510 AT CERN AND BNL

The MARS version m1510 has been compared, at CERN and BNL for a beam kinetic energy of 5 GeV.

Comparison for different particle types

In Table 3 the deviation $\mid N_{CERN} - N_{BNL} \mid / N_{CERN}$ per particle type, is given. Particle yields have been compared both at target (z = 0 m) and 50 m downstream of the target. The difference has been computed only when more than 100 particles were present at z = 0 m or 50 m. The deviation is not negligible for μ^- at z = 0 m, and π^- as well as ν_μ at z = 50 m. It cannot solely be explained by statistical fluctuations. The origin of the difference is un-

Table 3: Relative yield for m1510 at CERN and BNL.

Type	0 m	50 m
p	0 ± 0.01	0 ± 0.01
n	0 ± 0.01	-
π^+	0.01 ± 0.01	0.07 ± 0.02
π^-	0.01 ± 0.01	0.14 ± 0.03
K^+	0.02 ± 0.05	-
μ^+	0 ± 0.07	0.01 ± 0.01
μ^-	0.18 ± 0.07	0 ± 0.01
γ	0 ± 0.01	-
e^-	0.02 ± 0.01	0.02 ± 0.01
e^+	0.04 ± 0.01	0.02 ± 0.01
d	-	0.05 ± 0.07
ν_μ	0.04 ± 0.03	0.28 ± 0.12
$\bar{\nu}_\mu$	0.08 ± 0.04	0.03 ± 0.11
ν_e	0.04 ± 0.05	-

der investigation as it is suspected that different compiler versions may generate a shift in the random seeds used in the Monte-Carlo computation.

Muon yield in the Neutrino Factory acceptance

As a cross-check, for MARS version m1510, a set of 50 runs with different starting seeds has been computed, for 5 GeV kinetic energy of the beam, at CERN and BNL. The distribution of the muons with $40 < E^{\mu}_{kin} < 180$ MeV is given in Fig. 3 and 4. The value noted as RMS in the plot

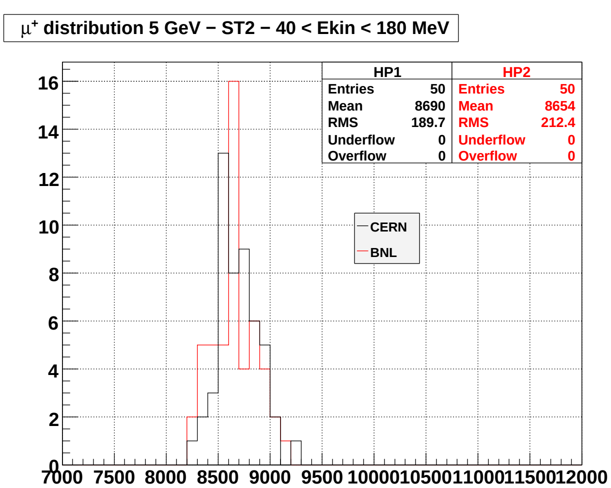

Figure 3: μ^+ distribution from 50 runs, with $40 < E^{\mu}_{kin} <$ 180 MeV at z = 50 m, for m1510 at BNL and CERN.

is in fact the standard deviation as calculated by ROOT [6] histogramming functions but named this way for historical reasons. The difference in the muon distribution between CERN and BNL, sits well within the statistical spread. The simulations for beam energies of 6 GeV to 15 GeV still need to be completed.

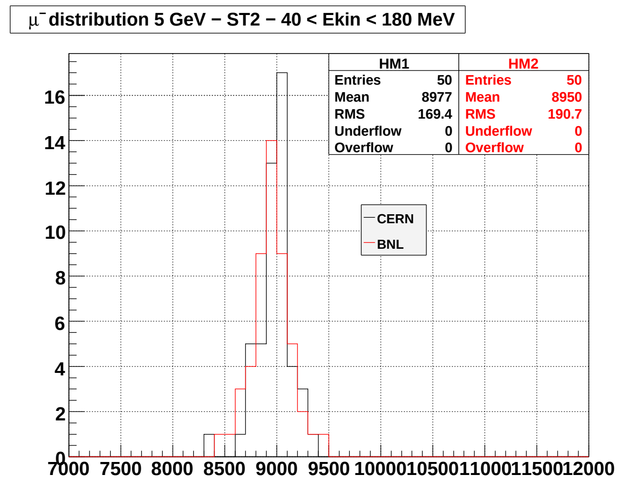

Figure 4: μ^- distribution from 50 runs, with $40 < E^{\mu}_{kin} <$ 180 MeV at z = 50 m, for m1510 at BNL and CERN.

CONCLUSION

Particle yields from MARS version m1507 and m1510 have been compared from simulations performed on CERN and BNL installations. The difference in yield for the same version of the code are not solely explained by statistical fluctuation and is investigated. These observed differences do not affect the production of the muons in the Neutrino Factory acceptance beyond a 10% level.

ACKNOWLEDGEMENT

We acknowledge the financial support of the European Community under the European Commission Framework Programme 7 Design Study: EUROnu, Project Number 212372. The EC is not liable for any use that may be made of the information contained herein.

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